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HIGH-STRENGTH CARBURIZED PART AND A METHOD OF THE SAME

The present invention claims foreign priority to Japanese patent application no. 2003-077356, filed on March 20, 2003, the contents of which is incorporated herein by reference.

BACKGROUND OF THE PRESENT INVENTION

1. Field of the present invention

The present invention relates to a carburized part and more particularly to a carburized part for a power transmission part such as a gear subjected to surface hardening before use or as a mechanical structural part requiring a pitting resistance.

2. Description of the Related Art

In the related art, there has heretofore been used a material according to JIS SCr420H as the material of a gear, which is a mechanical structural part used in a power transmission part for an automobile or the like.

A gear which is a mechanical structural part must meet requirements for high pitting resistance and strength of the tooth root (for example, fatigue strength and impact strength). To this end, the gear has been subjected to various related art surface treatments to enhance its strength before use.

Among these related art surface treatments, carburizing has been practiced as a method for providing high strength in particular. In recent years, carbonitriding has been used as

a method for improving pitting resistance and fatigue strength.

However, with the recent rise in output and the reduction of automobile size there has been a growing demand for the enhancement of the strength of mechanical structural parts such as the gear. Even when subjected to carburizing or carbonitriding, these mechanical structural parts often undergo pitting destruction or tooth root destruction. Thus, there is a related art need for further improvement in these mechanical structural parts.

The aforementioned pitting involves the occurrence of cracks and the subsequent progress of the cracks resulting in flaking attributed to high stress caused by the friction of the surface of mechanical structural parts with each other, e.g., the surface of the teeth of the gear. To attempt to prevent the occurrence of pitting destruction, tooth root destruction and the like, the related art practice has been to grind the sliding surface, such as the surface of the tooth, and remove defects such as the abnormal carburizing layer, thus enhancing the strength of the tooth. However, the cost of tooth grinding (grinding of the surface of tooth) can account for up to half of the production cost of the gear. Thus, the foregoing scheme is greatly disadvantageous in terms of cost.

In order to solve these related art problems, highly alloyed steel may be used as a gear material of gear to enhance the strength of the mechanical structural parts.

For example, Japanese Patent Unexamined Publication JP-A-2002-212672 discloses related art concerning a steel member. Mo is added as an element for increasing the precipitation of carbides and enhancing hardenability in an amount from 0.05 to 0.6%, preferably 0.15% or more for enhancing the pitting resistance of gear and sliding parts without impairing the bend fatigue properties.

Japanese Patent Unexamined Publication JP-A-6-158266 discloses related art concerning a process for the production of a high face pressure part. Mo and Ni are added in an amount of up to 1.0% and up to 3%, respectively, for the purpose of enhancing the pitting resistance of gear, etc.

However, the aforementioned approach involving the addition of a large amount of Ni, Mo, etc. for the purpose of enhancing strength disadvantageously causes high material cost, because these elements are expensive.

SUMMARY OF THE PRESENT INVENTION

The high-strength carburized part of the present invention has been proposed to solve these related art problems. However, it is not necessary for the present invention to solve these problems, or any other problems.

According to a first aspect of the present invention, a high-strength carburized part having a core having a chemical composition of

C: 0.15 to 0.30% by weight,
Si: 0.25 to 1.10% by weight,
Mn: 0.3 to 1.20% by weight,
Cr: 1.25 to 2.0% by weight and

a balance including unavoidable impurities and Fe;
a vacuum-carburized surface having a carbon ratio ranging from 1.0 to 1.5%, a region extending from the surface to a depth of 50 μ m and having a grain boundary oxide layer with a depth of 1 μ m or less, wherein a area ratio of carbides of the surface is from 5 to 15% and at least 90% of carbides have a grain size of 5 μ m or less and wherein the core comprises an interior region which cannot be carburized.

According to a second aspect of the present invention as set forth in the first aspect of the present invention, the core further has B and Ti in an amount of from 0.0005 to 0.0050% by weight and from 0.02 to 0.06% by weight, respectively.

According to third and fourth aspects of the present invention as set forth in the first and second aspects of the present invention, the core further has Nb in an amount of from 0.02 to 0.12% by weight.

According to fifth, sixth, seventh and eighth aspects of the present invention as set forth in the first, second, third, fourth aspects of the present invention, the core further has at least one of: Pb ranging from 0.01 to 0.20% by weight, Bi ranging from 0.01 to 0.10% by weight, Ca ranging from 0.0005

to 0.0050% by weight and S ranging from 0.005 to 0.100% by weight.

According to a ninth aspect of the present invention as set forth in the first aspect of the present invention, the chemical composition of Si is 0.60% by weight or less.

According to a tenth aspect of the present invention as set forth in the first aspect of the present invention, the chemical composition of Mn is 0.60% by weight or less.

According to an eleventh aspect of the present invention as set forth in the first aspect of the present invention, the core further includes at least one of: Cu in an amount of 0.30% by weight or less, Ni in an amount of 0.30% by weight or less and Mo in an amount of 0.05% by weight or less.

According to a twelfth aspect of the present invention as set forth in the first aspect of the present invention, the core further has at least one of the following:

B and Ti in an amount of from 0.0005 to 0.0050% by weight and from 0.02 to 0.06% by weight, respectively; and

Nb in an amount of from 0.02 to 0.12% by weight; and

Pb ranging from 0.01 to 0.20% by weight, Bi ranging from 0.01 to 0.10% by weight, Ca ranging from 0.0005 to 0.0050% by weight and S ranging from 0.005 to 0.100% by weight, wherein at least one of the following is true:

the chemical composition of Si is 0.60% by weight or less,

the chemical composition of Mn is 0.60% by weight or less

or

Cu in an amount of 0.30% by weight or less, Ni in an amount of 0.30% by weight or less and Mo in an amount of 0.05% by weight or less.

According to a thirteenth aspect of the present invention, a method of manufacturing a carburized part has steps of

working an alloy that includes 0.15 to 0.30% C by weight, 0.25 to 1.10% Si by weight, 0.3 to 1.20% Mn by weight, 1.25 to 2.0% Cr by weight and a remaining balance including unavoidable impurities and Fe into a shape of the carburized part;

vacuum-carburizing the alloy such that a C content on a surface of the alloy is from 1.0 to 1.5%.

According to a fourteenth aspect of the present invention as set forth in the thirteenth aspect of the present invention, in a region extending from a surface of the carburized part to a depth of 50 μm , an area ratio of carbides is ranging 5 to 15%, and at least 90% of carbides have a grain size of 5 μm or less and a grain boundary oxide layer with a depth of 1 μm or less.

According to a fifteenth aspect of the present invention as set forth in the thirteenth aspect of the present invention, the alloy further comprises B and Ti in an amount of from 0.0005 to 0.0050% by weight and from 0.02 to 0.06% by weight, respectively.

According to a sixteenth aspect of the present invention

as set forth in the thirteenth aspect of the present invention, the alloy further comprises Nb in an amount of from 0.02 to 0.12% by weight.

According to a seventeenth aspect of the present invention as set forth in the fifteenth aspect of the present invention, the alloy further comprises Nb in an amount of from 0.02 to 0.12% by weight.

According to an eighteenth aspect of the present invention as set forth in the thirteenth aspect of the present invention, the alloy further comprises at least one of: Pb ranging from 0.01 to 0.20% by weight, Bi ranging from 0.01 to 0.10% by weight, Ca ranging from 0.0005 to 0.0050% by weight and S ranging from 0.005 to 0.100% by weight.

According to a nineteenth aspect of the present invention as set forth in the fifteenth aspect of the present invention, the alloy further comprising at least one of: Pb ranging from 0.01 to 0.20% by weight; Bi ranging from 0.01 to 0.10% by weight; Ca ranging from 0.0005 to 0.0050% by weight or S ranging from 0.005 to 0.100% by weight.

According to a twentieth aspect of the present invention as set forth in the sixteenth aspect of the present invention, the alloy further comprising at least one of: Pb ranging from 0.01 to 0.20% by weight; Bi ranging from 0.01 to 0.10% by weight; Ca ranging from 0.0005 to 0.0050% by weight or S ranging from 0.005 to 0.100% by weight.

According to a twenty-first aspect of the present invention as set forth in the seventeenth aspect of the present invention, the alloy further comprising at least one of: Pb ranging from 0.01 to 0.20% by weight; Bi ranging from 0.01 to 0.10% by weight; Ca ranging from 0.0005 to 0.0050% by weight or S ranging from 0.005 to 0.100% by weight.

According to a twenty-second aspect of the present invention as set forth in the thirteenth aspect of the present invention, the alloy meets at least one of the following conditions: the chemical composition of Si is 0.60% by weight or less; and the chemical composition of Mn is 0.60% by weight or less; Cu is in an amount of 0.30% by weight or less, Ni is in an amount of 0.30% by weight or less and Mo is in an amount of 0.05% by weight or less.

According to a twenty-third aspect of the present invention, a gear for use in a power transmission, the gear is made of a material having a core having a chemical composition of

C: 0.15 to 0.30% by weight,

Si: 0.25 to 1.10% by weight,

Mn: 0.3 to 1.20% by weight,

Cr: 1.25 to 2.0% by weight and

a balance including unavoidable impurities and Fe;

a vacuum-carburized surface having a carbon ratio ranging from 1.0 to 15%, a region extending from the surface to a depth of

50 μm and having a grain boundary oxide layer with a depth of 1 μm or less, wherein a area ratio of carbides of the surface is from 5 to 15% and at least 90% of carbides have a grain size of 5 μm or less, and wherein the core comprises an interior region which cannot be carburized.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a diagram illustrating an example of processing pattern of high concentration vacuum carburizing which is executed to obtain a high strength carburized part of an exemplary, non-limiting embodiment of the present invention;

Fig. 2A is a diagram illustrating the test specimens used in the measurement of pitting life conducted in the non-limiting examples of the present invention;

Fig. 2B is a diagram illustrating the test specimens used in the measurement of fatigue strength conducted in the non-limiting examples of the present invention; and

Fig. 2C is a diagram illustrating the test specimens used in the measurement of Charpy absorption energy conducted in the non-limiting examples of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

The present invention will be further described in the following examples.

(a) Production of material

50 kg of a steel material having the composition set forth in Table 1 was melted in a vacuum induction furnace to cast an ingot iron which was then forged and extend to a diameter of 32 mm for machining.

The material was measured for various properties set forth in Table 2. The measuring conditions are as follows.

(b) Normalizing hardness

The material was machined to a rod specimen having a diameter of 25 mm and a length of 100 mm which was then normalized at 920°C for 1 hour and measured for normalizing hardness.

The measurement of normalizing hardness was conducted on the central part of a section of the rod specimen on B scale according to JIS Z 2245.

(c) Carburizing

The specimen to be evaluated for strength was subjected to vacuum carburizing in the following manner.

First stage: The specimen was subjected to carburizing such that the target of the percent uppermost C content on the surface is 1.2% to allow a considerably large amount of C to penetrate into the steel.

Second stage: To precipitate the carbon which has penetrated into the steel at the first stage, the specimen was subjected to precipitation at 850°C for 60 minutes.

The specimen thus carburized was then subjected to tempering at 180°C for 90 minutes.

(d) Surface carbon content

The specimen thus carburized was measured for percent C content from the turnings of the region extending from the surface thereof to a depth of 50 μm .

(e) Measurement of maximum carbide grain size, area ratio

The rod specimen which had been subjected to high concentration carburizing and tempering was cut at its longitudinally central position. The section of the rod specimen was polished, and then subjected to corrosion with a picral etching process. The specimen was then photographed under SEM at a position of 50 μm from the uppermost surface thereof (magnification: x 5,000). The photograph was then subjected to image analysis to determine the area ratio of carbide. The proportion of carbides having a diameter of 5 μm or less was also calculated.

(f) Presence or absence of network carbides and imperfect martensitic structures

The specimen was observed under the same conditions as mentioned above to see if network carbides and imperfect martensitic structures are present. The network carbides are coarse carbides (carbide having large grain size) precipitated in a network form along a grain boundary.

Table 1

Steel grades	Chemical component (wt-%)										
	C	Si	Mn	Cu	Ni	Cr	Mo	B	Ti	Nb	Others
A	0.20	0.50	0.50	0.14	0.07	1.75	0.01	-	-	-	-
B	0.16	0.51	0.55	0.11	0.08	1.73	0.01	-	-	-	Pb: 0.012
C	0.19	0.92	0.47	0.16	0.10	1.72	0.02	-	-	-	-
D	0.18	0.49	0.95	0.15	0.08	1.73	0.01	-	-	-	Ca: 0.0021 S: 0.049
E	0.20	0.51	0.51	0.14	0.08	1.32	0.03	-	-	-	-
F	0.19	0.48	0.49	0.16	0.09	1.97	0.02	-	-	-	Bi: 0.03
G	0.21	0.50	0.50	0.14	0.07	1.77	0.02	0.0016	0.034	-	N: 0.006
H	0.21	0.49	0.51	0.17	0.09	1.77	0.01	0.0015	0.035	0.049	N: 0.007
I	0.18	0.5	0.48	0.16	0.08	1.72	0.02	-	-	-	-
J	0.27	0.62	0.61	0.14	0.11	1.81	0.01	-	-	-	-
K	0.20	0.27	0.50	0.14	0.07	1.80	0.02	-	-	-	Pb: 0.015
L	0.21	1.02	0.53	0.17	0.10	1.78	0.01	-	-	-	-
M	0.20	0.50	0.26	0.13	0.08	1.75	0.01	-	-	-	-
N	0.20	0.51	1.12	0.14	0.08	1.30	0.02	-	-	-	Bi: 0.03
O	0.19	0.47	0.52	0.14	0.12	1.27	0.03	-	-	-	-
P	0.20	0.50	0.49	0.13	0.09	2.09	0.01	-	-	-	-
Q	0.20	0.20	0.70	0.15	0.10	1.05	0.02	-	-	-	-

Table 2

Example No.	Steel grades	Normalizing hardness		Surface carbon content		Area ratio of carbide		Area ratio of carbides having a grain size of 5 μm or less	Network carbide		Imperfect martensitic structure
		HRB		%		%			Presence or absence		Presence or absence
1	A	82.5		1.42		11.5		92.2	Absence		Absence
2	B	82.1		1.40		10.2		93.7	Absence		Absence
3	C	84.5		1.13		5.8		99.0	Absence		Absence
4	D	88.5		1.41		11.4		93.3	Absence		Absence
5	E	80.4		1.21		5.2		97.3	Absence		Absence
6	F	83.1		1.48		14.8		91.9	Absence		Absence
7	G	84.2		1.40		11.8		93.4	Absence		Absence
8	H	86.3		1.39		11.9		94.0	Absence		Absence
9	I	80.1		1.38		11.2		94.5	Absence		Absence
10	J	89.1		1.42		11.7		90.7	Absence		Absence
11	K	81.2		1.49		14.9		91.0	Absence		Absence
12	L	87.0		1.07		5.3		99.3	Absence		Absence
13	M	78.9		1.39		11.3		93.2	Absence		Presence
14	N	89.7		1.41		12.5		94.1	Absence		Absence
15	O	79.8		1.05		5.1		98.8	Absence		Absence
16	P	84.2		1.55		15.4		85.2	Presence		Presence

In Tables 1 and 2 above, the steel materials A to L, N and O satisfy the requirements of the present invention.

All these non-limiting embodiment examples exhibit a normalizing hardness HRB of less than 90 after normalizing and thus can be easily machined.

All these examples satisfy the requirements of the present invention after carburizing and show no production of imperfect martensitic structures causing the deterioration of strength and a small area ratio of coarse carbides.

On the contrary, the steel materials M and P are comparative examples which do not satisfy the requirements of the present invention, as discussed below.

The steel material M has too low an Mn content. Thus, the resulting carburized layer has imperfect martensitic structures formed therein.

This is presumably because the content of Mn is too small to provide the carburized layer (particularly around carbides) with a sufficient hardenability.

The steel material P has too large a Cr content and thus can be easily carburized. The percent surface carbon content of the steel material P exceeds the upper limit as defined in the present invention.

As a result, the content of carbides increases, causing the precipitation of coarse carbides having a grain size of more than 5 μm .

The steel material P had imperfect martensitic structures observed around carbides.

Table 3 shows the carburizability of the steel material A in Table 1 obtained when subjected to high concentration vacuum carburizing such that the target surface carbon concentrations (% surface carbon content) are 0.8%, 1.2%, 1.4%, 1.6% and 1.8%.

The measuring method is the same as mentioned above.

Table 3

Example No.	Steel grades	Surface carbon concentration	Area ratio of carbide	Area ratio of carbides having a grain size of 5 μm or less	Network carbide	Imperfect martensitic structure
		%	%		Presence or absence	Presence or absence
17	A	0.83	1.2	99.8	Absence	Absence
18	A	1.21	5.7	97.2	Absence	Absence
19	A	1.42	11.5	93.9	Absence	Absence
20	A	1.56	12.2	89.1	Presence	Absence
21	A	1.83	18.0	81.6	Presence	Presence

Example No. 18 and 19 satisfy the requirements of the present invention and show no production of imperfect martensitic structures causing the deterioration of strength and a small area ratio of coarse carbides.

On the contrary, Example No. 17 is a comparative example having a low surface carbon concentration and shows an extremely small precipitation of carbides.

Example No. 20 and 21 are comparative examples having a surface carbon concentration higher than the range defined in the present invention and thus having a large amount of coarse carbides.

In particular, Example No. 21 shows much precipitation of carbides, causing the deterioration of the hardenability of the matrix. The resulting carburized layer had imperfect martensitic structures observed therein.

The various steel materials set forth in Table 1 were each subjected to vacuum carburizing (under the same conditions as mentioned above). The steel materials thus carburized were each measured for hardness, depth of grain boundary oxide layer, fatigue strength, pitting life and Charpy absorption energy.

The results are set forth in Table 4.

The conditions under which these tests are conducted will be described below.

Table 4 also shows the results obtained when atmospheric gas carburizing is conducted for comparison.

(a) Preparation of test specimen

The roller pitting test specimen 10 shown in Fig. 2(A), the rotary bend test specimen 12 shown in Fig. 2(B) and the Charpy impact test specimen 14 shown in Fig. 2(C) were prepared.

For the preparation of the rotary bend test specimen 12, an Ono type rotary bend fatigue test specimen having annular cutouts having r of 1 mm (stress concentration coefficient $\alpha_k = 1.8$) was prepared. The test specimen was then subjected to carburizing in the manner as mentioned above before test.

Some of these test specimens were subjected to S/P (shot peening) at an arc height of 1 mmA.

(b) Test conditions

[Hardness]

The roller pitting test specimen 10 was measured for hardness at a depth of 50 μm from the transferring surface thereof according to JIS Z 2244 (HV0.3).

[Depth of grain boundary oxide layer]

The transferring surface of the roller pitting test specimen 10 was polished, and then observed left uncorroded. The depth of layer seen as black along the grain boundary was then measured.

[Roller pitting test]

The roller-pitting test was conducted at a face pressure of 3.4 GPa, a rotary speed of 1,500 rpm, a percent slip ratio of -40% and an oil temperature of 80°C.

[Rotary bend test]

The Ono type rotary bend test was conducted at a rotary speed of 3,500 rpm and room temperature.

The stress at which the test specimen cannot be broken even when rotated at 10^7 cycles was defined as fatigue strength.

[Charpy impact test]

The notch used was a 10R notch.

Table 4

Example No.	Steel grades	Carburizing conditions	Other treatments	Hardness (HV)	Depth of grain boundary oxide layer (μm)	Fatigue strength (MPa)	Pitting life ($\times 10^6$ cycles)	Charpy absorption energy (J)
		Vacuum or atmosphere						
22	A	Vacuum	-	757	0.2	598	8.7	98.7
23	B	Vacuum	-	759	0.1	552	8.2	105.3
24	C	Vacuum	-	742	0.2	569	8.5	100.5
25	D	Vacuum	-	763	0.3	632	9.0	79.3
26	E	Vacuum	-	740	0.2	543	7.8	107.2
27	F	Vacuum	-	783	0.2	640	9.3	93.8
28	G	Vacuum	-	769	0.1	612	8.9	115.3
29	H	Vacuum	-	772	0.3	635	9.2	120.9
30	I	Vacuum	-	762	0.1	473	7.4	105.0
31	K	Vacuum	-	801	0.2	480	8.4	69.2
32	L	Vacuum	-	733	0.2	567	5.1	97.3
33	M	Vacuum	-	662	0.1	389	2.6	80.3
34	O	Vacuum	-	734	0.2	498	4.9	89.4
35	P	Vacuum	-	674	0.1	507	2.6	67.4
36	Q	Atmosphere	-	728	13.4	402	2.7	35.7
37	A	Atmosphere	-	732	5.1	459	5.5	46.7
38	A	Vacuum	S/P	792	Not executed	699	10.9	128.4
39	Q	Atmosphere	S/P	780	Not executed	558	5.0	52.4

In Table 4 above, the steel material Q corresponds to steel according to JIS SCr420H.

Example No. 22 to 32, 34, and 38 in Table 4 satisfy the requirements of the present invention.

These examples exhibit hardness equal to or higher than that of carburizing steel according to JIS SCr420H (Example No. 36, which comprises the steel material Q of Table 1).

These examples also exhibit a fatigue strength of about 1.5 times that of Example No. 36, a pitting life of about three times that of Example No. 36 and an impact strength of about twice that of Example No. 36.

Example No. 38 is the same as Example No. 22 except that the material is subjected to S/P and exhibits excellent strength properties as compared with Example No. 39, which corresponds to carburizing steel according to JIS SCr420H (No. 36) subjected to S/P.

Example No. 33, 35 to 37, and 39 are comparative examples which do not satisfy the requirements of the present invention.

Example No. 33 (which comprises the steel material M set forth in Table 1) has imperfect martensitic structures formed therein and exhibits deteriorated fatigue strength and pitting life.

Example No. 35 (which comprises the steel material P set forth in Table 1) exhibits has imperfect martensitic structures formed therein and thus exhibits a deteriorated surface hardness

and hence a reduced pitting life.

The steel materials which have been subjected to atmospheric carburizing (Example Nos. 36 and 37) have a deep grain boundary oxide layer formed therein and thus exhibit deteriorated impact strength.

As mentioned above, the essence of the present invention is the part having the treatment of the present invention avoids the need for adding an expensive element such as Mo and Ni. High concentration carburizing is conducted to cause carbides to separate out on the surface of gear or the like in a slight amount, enhancing the surface hardness and strength. Vacuum carburizing is conducted to substantially eliminate the grain boundary oxide layer on the surface.

In the present invention the content of C is slightly raised. Cr, which is a carbide-forming element, is added in a slightly raised amount and Si is added in a slightly raised amount to enhance the temper softening resistance. The surface carbon concentration after carburizing is as high as from 1.0 to 1.5%, the area ratio of carbides is from 5% to 15%, wherein carbides having a grain size of 5 μm or less account for the most part (90% or more) of all the carbides. Further, vacuum carburizing is conducted to form a grain boundary oxide layer to a depth of 1 μm or less.

Focusing on the pitting mechanism that a brittle Cr or Si oxide layer is formed along grain boundary to lower the

strength of the grain boundary from which cracks start to occur and then proceeds to flaking, in the present invention vacuum carburizing is conducted to substantially eliminate brittle oxide layer in grain boundary (forming a grain boundary oxide layer to a depth of 1 μm or less) and hence prevent the progress of cracks from the grain boundary due to a brittle oxide layer formed in grain boundary. High concentration carburizing is conducted to cause carbides to separate out on the surface in a slight amount, resulting in precipitation hardening that enhances the surface hardness and strength.

However, even if high concentration carburizing is conducted to enhance surface carbon concentration and hence cause carbides to separate out, when the resulting carbides are coarse, they occur in a networked form along a grain boundary, weakening the strength of the grain boundary.

Therefore, in accordance with the present invention, the surface carbon concentration is kept within a range of from 1.0% to 1.5% and the percent carbide area is from 5% to 15%. On the other hand, carburizing is controlled such that carbides having a grain size of 5 μm or less account for 90% or more of all the carbides. In this arrangement, the enhancement of the strength of surface and grain boundary by the precipitation of carbides can be accomplished, making it possible to effectively enhance the pitting resistance of the surface of gear, etc.

In accordance with the present invention, surface grinding such as tooth grinding can be substantially eliminated. Combined with the arrangement that an expensive element such as Mo and Ni is not added, the omission of surface grinding provides a high-strength carburized part at a reduced cost.

In the second aspect of the present invention, B and Ti may be further incorporated in the material in an amount of from 0.0005 to 0.0050% and from 0.02 to 0.06%, respectively, as necessary.

In the third aspect of the present invention, Nb may be further incorporated in the material in an amount of from 0.02 to 0.12%.

Moreover, in the fifth aspect of the present invention, any of from 0.01 to 0.20% by weight of Pb, from 0.01 to 0.10% by weight of Bi, from 0.0005 to 0.0050% by weight of Ca and from 0.005 to 0.100% by weight of S may be incorporated in the material as necessary.

The reason for the limitation of the various chemical components in the present invention will be described in detail hereinafter.

C: 0.15 to 0.30% by weight

C is essential for the enhancement of the strength of non-carburized layer. To this end, C needs to be incorporated in an amount of 0.15% or more.

On the other hand, when C is incorporated in the material

in an amount of more than 0.30%, the resulting rise of the hardness of the core causes deterioration of cold forging workability or machinability. Thus, the content of C is 0.30% or less.
Si: 0.25 to 1.10% by weight

Si has an effect of enhancing the pitting resistance of the material by atomizing carbides and enhancing temper-softening resistance. For this effect, Si is incorporated in the material in an amount of 0.25% or more.

On the contrary, when C is incorporated in the material in an amount of more than 1.10%, the resulting rise of the hardness of the core causes deterioration of cold forging workability or machinability. Further, Si impairs the ability of the material to be carburized, thus prolonging the carburizing. Thus, the upper limit of the content of Si is 1.10%.

The upper limit of the content of Si is preferably 0.60% or less.

Mn: 0.3 to 1.20% by weight

Mn is effective for the enhancement of strength of the core and hardenability. To this end, Mn needs to be incorporated in the material in an amount of 0.3% or more. When the content of Mn falls below the above-defined range, the resulting carburized product has too low a hardenability that causes the production of imperfect martensitic structure in the vicinity of carbide.

On the contrary, when Mn is incorporated in an amount

of more than 1.20%, the resulting rise of the hardness of the core causes deterioration of cold forging workability or machinability. Thus, the upper limit of the content of Mn is 1.20% or less.

The content of Mn is preferably 0.60% or less.

Cr: 1.25 to 2.0%

Cr needs to be incorporated in the material as a carbide-forming element or an element for enhancing hardenability in an amount of 1.25% or more.

On the contrary, when Cr is incorporated in the material in an amount of 2.0% or more, the resulting rise of the hardness of the core causes deterioration of cold forging workability or machinability. Further, coarse carbides are produced in a large amount. Thus, Cr is incorporated in the material in an amount of 2.0% or less in the present invention.

B: 0.0005 to 0.0050%

B acts to enhance hardenability and toughness, increasing the impact strength and fatigue strength of the tooth root. Thus, B is incorporated in the material in an amount of 0.0005% or more as necessary.

However, since the effect is saturated to economic disadvantage even when B is incorporated in the material in an amount of more than 0.0050%, the upper limit of the content of B is 0.0050%.

Ti: 0.02 to 0.06%

Ti forms a nitride to prevent B from forming a nitride and thus is effective to assure that B can exert an effect of enhancing hardenability and toughness.

However, when the content of Ti is less than 0.02%, Ti cannot exert its effect. On the contrary, when Ti is incorporated in the material in an amount of 0.06%, the effect of Ti is saturated. Therefore, the addition of Ti in an amount of more than 0.06% is economically disadvantageous. Thus, the upper limit of the content of Ti is predetermined to be 0.06% even when Ti is incorporated with B.

Nb: 0.02 to 0.12%

Nb acts to inhibit the growth of crystallites and hence the production of coarse carbides that causes deterioration of fatigue strength during treatment at a temperature as high as about 1,000°C. In order to exert this effect, Nb needs to be incorporated in the material in an amount of 0.02% or more.

On the contrary, when Nb is incorporated in the material in an amount of more than 0.12%, coarse carbides are formed during solidification, eliminating the effect of inhibiting the growth of crystallites and deteriorating the strength of the product. Thus, the upper limit of the content of Nb is 0.12%.

Pb: 0.01 to 0.20%

Bi: 0.01 to 0.10%

Ca: 0.0005 to 0.0050%

S: 0.005 to 0.100%

These elements enhance workability and are incorporated in the material as necessary.

However, when these elements are incorporated more than necessary, the resulting product exhibits a deteriorated strength. Thus, the upper limit of the content of these elements is defined above.

Electric furnace steel-making using scrap as starting material involves the unavoidable incorporation of impurities such as Cu, Ni and Mo.

When the content of these impurities is limited to an extremely low level, it adds to cost. Therefore, the incorporation of these impurities to some extent is acceptable in the present invention.

However, the content of these components is preferably limited as follows.

Cu: $\leq 0.30\%$

Cu raises the hardness of the core of the material, causing the deterioration of cold forging workability or machinability of the material. Therefore, it is preferred that the content of Cu be limited to 0.30% or less.

Ni: $\leq 0.30\%$

Ni raises the hardness of the core of the material, causing the deterioration of cold forging workability or machinability of the material. Therefore, it is preferred that the content

of Ni be limited to 0.30% or less.

Mo: $\leq 0.05\%$

Mo drastically raises the hardness of hot-worked or normalized material. Accordingly, Mo is not a positive additive in the present invention, which is intended to accomplish productivity and strength at the same time.

Therefore, it is preferred in the present invention that the content of Mo be limited to 0.05% or less.

The above-defined content of Cu, Ni and Mo are all on the impurity level in electric furnace steel making.

Carburizing: vacuum carburizing (1,000 Pa or less)

The carburized part of the present invention is produced by vacuum carburizing.

The elimination of a grain boundary oxide layer by vacuum carburizing makes it possible to enhance the strength of the carburized part.

In the present invention, Si is incorporated in the material as an essential chemical component.

Si is an element that accelerates the oxidation of the grain boundary during ordinary carburizing in the atmosphere. The resulting Si grain boundary oxide layer causes the deterioration of impact strength or fatigue strength of the tooth root. Accordingly, Si cannot be incorporated in the material in a large amount in ordinary atmospheric carburizing.

However, when the carburized part is produced by vacuum

carburizing, the production of such a grain boundary oxide layer is inhibited. Thus, Si can be incorporated in the material in a large amount. Thereby, the resulting carburized part exhibits an enhanced temper softening and hence an enhanced pitting strength and strength of root of tooth.

When high concentration carburizing is conducted by a conventional atmospheric gas carburizing method, sooting can occur, causing the occurrence of uneven carburizing. However, when vacuum carburizing is conducted, the occurrence of uneven carburizing can be inhibited.

Depth of grain boundary oxide layer: 1 μ or less

A grain boundary oxide layer causes the deterioration of fatigue strength and pitting resistance. Thus, the greater the depth of grain boundary oxide layer, the greater the degree of the deterioration of fatigue strength and pitting resistance.

In the present invention, it is necessary that the depth of grain boundary oxide layer after vacuum carburizing is 1 μm or less.

Distribution of carbides:

Ratio of carbides: from 5 to 15% over a region from the surface thereof to a depth of 50 μm

Proportion of carbides having a grain size of 5 μm or less: 90% or more of the total number of carbides

The precipitation of carbides causes the enhancement of surface hardness and hence strength.

However, when the amount of carbides over a region from the surface to a depth of 50 μm falls below 5%, the desired effect of enhancing strength cannot be sufficiently exerted. On the contrary, when the amount of carbides over a region from the surface to a depth of 50 μm exceeds 15%, elements such as Cr are contained in carbides, causing the occurrence of a Cr-lacking layer in the matrix. Thus, the resulting matrix lacks hardenability, causing the production of troostite around carbides and resulting in the deterioration of strength of the product.

Even if the requirement for percent carbide area (from 5% to 15%) is met, when coarse carbides having a grain size of more than 5 μm are produced in an amount of more than 10%, they form a network carbide along the grain boundary, that is, a grain boundary having cutouts formed therein, causing the deterioration of strength of the product.

Accordingly, in the present invention, it is necessary to precipitate finely divided carbides such that a number of carbides having a grain size of 5 μm or less account for 90% or more of the total number of carbides.

Surface carbon content: 1.0 to 1.5%

The percent surface carbon content is a factor governing the precipitated amount and grain size of carbides. When the percent surface carbon content falls below 1.0%, the precipitated amount of carbides is too small to exert a

sufficient effect of enhancing strength.

On the contrary, when the percent surface carbon content exceeds 1.5%, the amount of carbides exceeds 15%; the resulting matrix lacks hardenability and thus exhibits a deteriorated strength.

Thus, the surface carbon content is limited to a range of from 1.0% to 1.5%.

Shot peening (S/P), water jet peening (W/J):

In the present invention, S/P or W/J may be conducted as necessary.

Carburizing pattern:

The carburized part of the present invention can be obtained by subjecting the material to high concentration vacuum carburizing in a processing pattern as shown in Fig. 1 for example.

At a first stage, the material is subjected to carburizing in an atmosphere the carbon potential (C_p) of which has been adjusted to about 1.5% at a temperature of about 950°C. Subsequently, at a second stage, the material is kept in an atmosphere the carbon potential of which has been adjusted to about 0.8% at a temperature of about 850°C for 2 hours. The material is then subjected to oil quenching.

While there has been described in connection with the preferred embodiments of the present invention, it will be obvious to those skilled in the art that various changes and

modification may be made therein without departing from the present invention, and it is aimed, therefore, to cover in the appended claim all such changes and modifications as fall within the true spirit and scope of the present invention.